Experiments and Mathematical Modeling of Blindfolded Walking

THESIS

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Abstract

In an environment full of visual reference objects, it is easy for normal human to use vision to walk in a straight line for a fairly long time and distance. When the environment lacks reference sources (e.g. as in a desert, forest, meadow), or when external visual information is not available to the subjects, the subjects would tend to walk in non-straight-line paths (e.g., circles) even though they intend to go in straight lines. This research aimed to better understand the relation between vision and walking directional stability by using data collected from experiments to construct a mathematical model that can (at least approximately) predict people's movements under blindfolded (or other no vision) situations. The experiments had two parts. In the first part, the subjects were asked to carry a GPS and walk on an open field while blindfolded. We found that the walking trajectories in these blind-folded outdoor experiments were far from straight-lines, with the subjects walking in curved paths with typical radius of curvature 8.8 m (mean over all subjects and trials). In the second part, the subjects were asked to walk as straight as possible from one end of the lab (indoors) to the other, again blindfolded. Several markers were put on the lower body of the subject. The lower body and pelvis movement were captured by the motion capture system. The data were processed by Matlab and used in the generation of mathematical model that relates body orientation to foot position. The mathematical model predicts the body position and heading angle, given the body position and heading angle of the previous step, including the noise and variability in the motion as measured in the indoor motion capture session. The simulated trajectories generated by the mathematical model were compared against the trajectories exhibited by the subjects on the field and we find that the simulated trajectories also have a substantial curvature. Thus, the simple model captures the experimental trajectories at least qualitatively, but there were quantitative differences between model predictions and data; a model that includes more state variables may be better. Understanding the role of vision in walking directional stability is an important part of a holistic understanding of human walking stability. A good model of human walking stability can be used as a tool for future researchers to develop medical devices to help those who have walking deficiencies or movement disorders.

Dedication

Dedicated to The Ohio State University

Acknowledgments

First and foremost, I would like to thank my research advisor, Professor Manoj Srinivasan, for his support and guidance throughout the research process over the last three semesters. He showed great patience in answering all the questions I have about my research and other academic issues in general. I have learned a lot by working with him. This research would have never been accomplished without his assistance. Thanks also to Prof. Kiran D'Souza for serving on the committee and to Prof. Robert Siston for the course on honors research.

I also want to thank all the members of the Movement Lab for providing valuable suggestions regarding my research works. Special thanks to Nidhi Seethapathi for showing me the operation of Vicon system.

In addition, I truly appreciate the time contributed by all of my subjects to help me finish the data collection.

I would also like to thank the College of Engineering at The Ohio State University for providing scholarship funds to support my research works.

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Chapter 1: Introduction

1.1 Background

It is not difficult for a normal person to walk in a straight line in a common environment for a long distance and time, with his eyes open. This common environment must have sufficiently many external visual reference sources to help the subject walk in the straight direction. When the environment lacks reference sources, or when external visual/auditory information is not available to the subjects, the subjects would get lost and tend to walk in circles, or more generally, in some non-straight-line paths, even though they intend to go in straight lines [1]. Research has suggested that this turning behavior is unrelated to postural asymmetry or functional dominance, but may be related to the subjects' body reactions to vestibular information [2]. It turns out that the blindfolded subjects are able to walk in an accurate straight line for a short distance, using their "body cues such as vestibular information and proprioception to sense their walking direction." [1] However, when these subjects are being asked to walk for a long distance, those internal body cues are no longer reliable and the walking direction may be disturbed by the accumulation of sensory noise [3, 4].

The balance of one's body determines its walking stability, which affects the subject's ability to walk in a straight line. The balance is the result of many body systems working together. There are some key factors that can affect the ability of subjects to walk straight. One is the accessibility of external directional reference. Souman et al [1] did experiments on many subjects (with sight and not blindfolded) by asking them to walk in a straight line in a large flat forest, both on cloudy days and sunny days. Those who did it on cloudy days continuously veered their moving directions, ended up lost in the forest and tended to walk in circles. However, those who could see the sun followed an accurate straight course. The author also asked their subjects to walk in Sahara desert, both during daytime and at night. The results were similar to the forest experiment, in which the subjects did much better during daytime than at night [1]. The results are illustrated in figure 1. It shows the importance of external directional references in maintaining one's course.

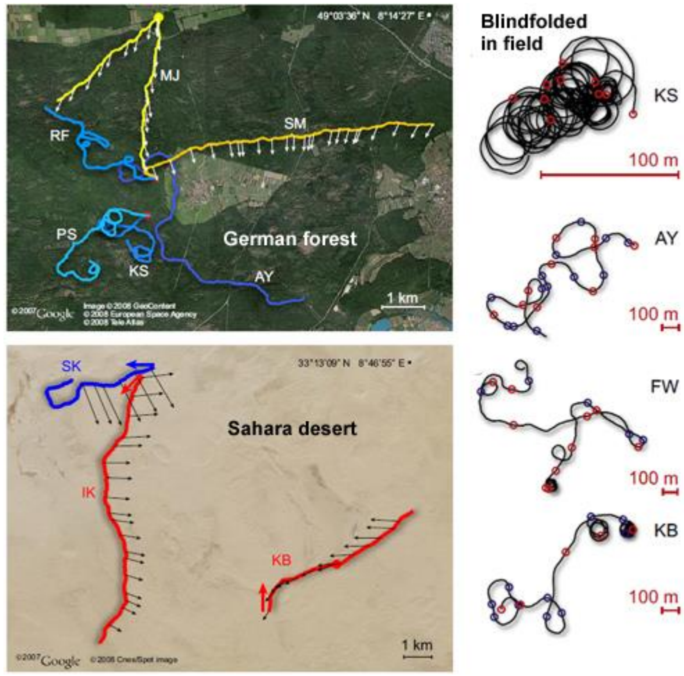

Figure 1: *Walking Trajectories of subjects in Souman et al's experiment [1]*

Another factor is the walking distance. Experiments showed that even when the subjects were blindfolded, they could still manage to walk in an almost perfect straight line relying on vestibular information and proprioception for a short distance (≤ 20m). These body cues became unreliable as the waking distance increased [1,6].

In addition to the above two factors, step frequency can also affect the walking stability. Azusa Uematsu et al [3] found that step frequency affects the magnitude of veering during natural human walking. Blindfolded subjects walked at preferred frequency experienced less veering than those who walked at low/high frequencies [5].

1.2 Focus of Thesis

A few researchers have attempted to provide biological explanations for this veering behavior [7,8]. Scientists have observed the veering behavior under different conditions and have sought to understand the relationships between neurological systems and external factors, and how the effects of external factors affect one's behavior.

The purpose of our research was to investigate the blindfolded walking behavior by combining human subject experiments with mathematical modeling. We seek to understand the human walking behavior by simply studying the behavior of the subjects during the experiments rather than seeking answers from a neurological point of view.

1.3 Research Objectives & Significances

Human body is a highly complicated system that involves many body parts working together neurologically and physically. Human walking is a stochastic dynamical system in which the representative equations of motion have an element of noise and randomness, thus making it very complex. Blindfolded walking, or in a more general case, walking without vision/effective external references, is part of the whole human walking behaviors that is not unusual in our daily life. This study is being performed as part of a broader search to understand human locomotion. The major objectives of this research are as follows:

- Generate mathematical models that can simulate and predict people's walking behavior under blindfolded situation
- Understand the effect of vision and the role of inherent noise in stability of walking direction
- Provide information for better understanding of human walking behavior as a stochastic dynamic systems
- And eventually, provide a basis for future studies possibly in development of medical applications, biomimetic robots and exoskeletons, etc., or assistive devices for individuals with visually impairments.

Knowing that human walking behavior is highly complicated, mathematical modeling can greatly simplify the problems and help bring some hidden phenomenon to surface. Although the mathematical model cannot perfectly duplicate the actual blindfolded walking behaviors, we hope that the quantitative results generated from the mathematical model provide intelligible understanding of the blindfolded walking behavior and contribute to a more complete understanding of human walking behavior in general.

1.4 Overview of Thesis

This thesis has 7 chapters. Chapter 2 discusses the methodology of data collection. This chapter consists of the detailed explanation of the experiment design, including experiment devices and software, criteria for subject selection and the actual experiment process. This research has two experiments for data collection. Chapter 3 focuses on the data processing procedures that transfer the raw data into clean and organized data that can be directly used for the model generation in Matlab. This chapter demonstrates some of the key techniques and theories behind data processing as well as a few Matlab functions specifically written for this research. Chapter 4 discusses the mathematical modeling, how the mathematical model is obtained, as well as the detailed procedure of prediction. Chapter 5 discusses the results of the research and compares the simulated results from the mathematical model to the experimental results from the experiment. Chapter 6 concludes the thesis and summarizes the key contributions of this research. It also discusses the possible applications of the mathematical model and proposes for possible future plans of the topic.

Chapter 2: Methodology

The experiments of this research were designed to collect necessary data for mathematical model generation and validation. All experiments done during the research were approved by the Institutional Review Board (IRB) at The Ohio State University. The participation in this study was completely voluntary.

2.1 Subject Selection

Criteria for sample inclusion: Healthy adults of both sexes, ages from eighteen to sixty. The subject must be able to walk and run at moderate speeds independently.

Criteria for sample exclusion: People who do not meet the criteria for inclusion should not participate in this research. In addition, pregnant women and those who have a history of heart or lung diseases or other movement disorders should not participate in this study.

Eight subjects participated with informed consent. Six of them participated in all of the experiments and two of them participated partially. This sample size should provide a good spectrum of healthy adults. In a sample size of 8 to 12, one might expect behaviors exhibited by only 20% of the general population to be observed in at least one subject in the sample with a probability of about 90%, assuming unbiased sampling.

The subjects’ age, height and body weight were measured and recorded. The environmental conditions of the experiment days were recorded for possible future studies.

2.2 Experiments Design

2.2.1 Outdoor Walking Trials Capture

To have a rough idea of the blindfolded walking behavior of the subjects, they were first asked to do an outdoor walking experiment. The outdoor walking experiment was designed to study the walking trials of the subjects, both with their eyes open and blindfolded, on a large flat open field. We planned to compare the data collected from the outdoor experiment to the results generated from the mathematical model.

2.2.1.1 Experiment Procedures

The outdoor experiment was conducted at Fred Beekman Park. The surface was flat and uniformly turfed. There was no obstacles on the ground so that tripping or bumping into things was avoided. Subjects carried a GPS in a waist pack or in their own coat pocket and worn a bicycle helmet covered with tin foil paper and attached with an external antenna for better GPS accuracy.

Figure 2: *Outdoor Experiment Location: Fred Beekman Park*

Figure 3: *Blindfolded subject wearing GPS in a waist with external antenna on a bicycle helmet*

Figure 4: *VBOX mini GPS*

First, the subjects were asked to walk as straight as possible in a given direction for approximately 100 meters with their eyes open. Then, the subjects were blindfolded and taken to a new starting point. All subjects were asked to wait approximately 1 minute before they were instructed to start the blindfolded walking. People may still have the memory of the surroundings for a short period of time after they were blindfolded, which might make their initial motion slightly different from the rest of the motion. The purpose of this waiting period was to control for any effect this memory may have on subjects' performances. After the waiting, subjects were asked to start walking as straight as possible for approximately 100 meters. Some trials were interrupted at relatively short distances if the subject walked close to the edge of the field and had a potential risk of falling or hitting the trees. After each trial, the subjects were lead to the next starting position, facing a randomly picked walking direction and started walking again. Each subject did at least five blindfolded trials. Subjects were blindfolded throughout all of the blindfolded trials so that they were not able to adjust their behavior based on their previous performance. For the same reason, between trials, the subjects were not given any feedback regarding whether they veered to the right or to the left on the previous trials.

The GPS device used in this experiment was a VBOX mini 10Hz data logger. It has an accuracy of 0.05% (<50cm per km) and a resolution of 1 centimeter. The accuracy of the GPS highly depends on the number of satellites it could detect and the distance between the GPS and the surrounding objects (trees, buildings etc.). The GPS worked well most of the time during the experiment and the noises it picked up were within the acceptable range.

2.2.1.2 Collected GPS Data

The GPS collected and reported at 10Hz sampling rate the following quantities: positions (as in latitudes and longitudes), velocities, heading direction estimates, altitude etc. For the purpose of this research, only the positions and velocities were used in the data processing.

2.2.2 Indoor Motion Capture

The indoor experiment was designed to collect data that were used in mathematical model generation. The detailed movements of the subjects were captured by Vicon motion capture system.

2.2.2.1 Experiment Procedures

The indoor experiment was conducted in Scott Lab. The room was cleared out to make space for the experiment. The subjects were asked to wear 9 markers, 3 on the front torso and 3 on each foot. Eight Vicon T20 motion capture cameras were set up facing against the walking direction of the subjects in order to capture the markers on the front.

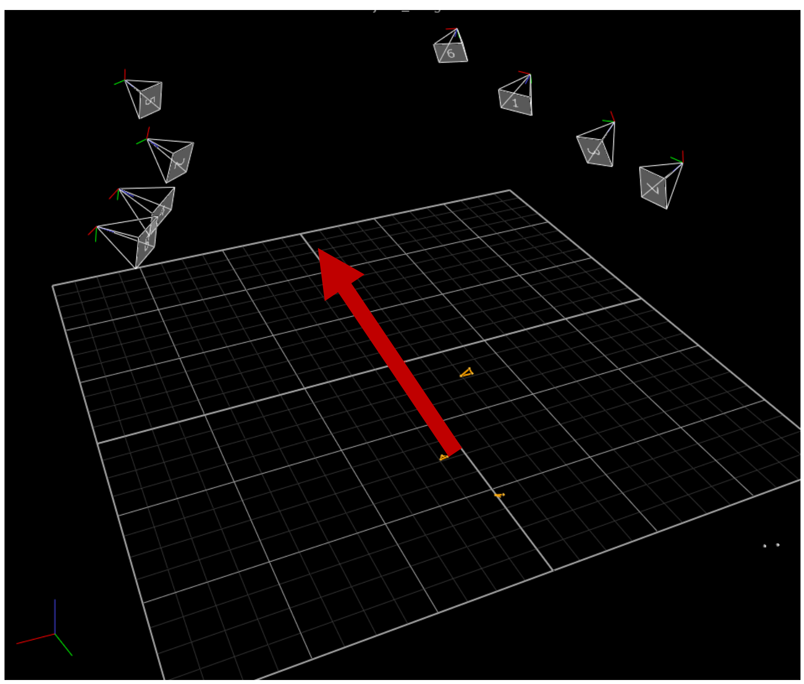

Figure 5: *Vicon Cameras set up as presented in Vicon Nexus*

Figure 6: *Vicon T20 Motion Capture Camera*

Figure 7: *Subject wearing marker on Torso and Both Feet*

Before the experiment, Vicon cameras were calibrated for the best capturing range. An origin was set at approximate the center of the room and was used for all trials of all subjects. Since this research only concerns about the steady-state walking behavior, the acceleration and deceleration stages of the walking trials were not included in the motion capture. Thus, the starting point and end point of the trials were set beyond the capturing range of the Vicon cameras. Each trial had about 5 “steady state” steps that were used for model generation.

For the first half of the indoor experiment, the subjects were asked to walk from the starting point to the end point with their eyes open for at least 20 times. Only the forward trials were captured. In the second half of the experiment, the subjects were blindfolded and repeated the trials for the same number of times. Each time the subject reached the end of the room or walked out of the capturing range of the cameras, the researcher would stop the subject and bring him/her back to the starting point. All trials were recorded by video for future analysis.

2.2.2.2 Collected indoor motion capture data

The detailed three dimensional time-history positions (X, Y, Z coordinates) of each marker with respect to the origin were recorded by the Vicon cameras.

Chapter 3: Data Processing

Data from both experiments were processed using multiple software including VBOX Tools (GPS data), Vicon Nexus (indoor mocap data) and MATLAB.

3.1 Outdoor Experiment Data Processing

The position data stored in VBOX were latitudes and longitudes by default. Although latitudes and longitudes are common geographic coordinate system that can easily define one's location on earth, they are hard to use for the calculations in this research. Therefore, longitudes and latitudes were first transferred into global rectangular coordinates then to local rectangular coordinates. The detailed procedures are demonstrated below.

First, we convert the longitudes and latitudes into global XYZ coordinate system, with the origin at the center of the earth using the classical formulas for spherical coordinates. In this calculation, R is the radius of earth and both latitude and longitude are in degrees:

$$X = R * \cos(latitude) * \cos(longitude)$$

$$Y = R * \sin(latitude)$$

$$Z = R * \cos(latitude) * \sin(longitude)$$

Next, axes of local coordinate system were defined with local Z axis being the line from the center of the earth to the first data point of each trial (approximately, normal to the earth surface) and the local Y axis aligned with geographic north.

$$\mathrm{ZAxis} = \left[\cos\left(\mathrm{longitude}(1)\right) * \cos\left(\mathrm{latitude}(1)\right), \sin\left(\mathrm{longitude}(1)\right) * \cos\left(\mathrm{latitude}(1)\right), \sin\left(\mathrm{latitude}(1)\right)\right]$$

$$\mathrm{YAxis} = \left[-\sin\left(\mathrm{latitude}(1)\right) * \cos\left(\mathrm{longitude}(1)\right), -\sin\left(\mathrm{latitude}(1)\right) * \sin\left(\mathrm{longitude}(1)\right), \cos\left(\mathrm{latitude}(1)\right)\right]$$

$$\mathrm{XAxis} = \mathrm{cross}(\mathrm{YAxis}, \mathrm{ZAxis})$$

$$\mathrm{localAxes} = [\mathrm{XAxis};\ \mathrm{YAxis}, ; \mathrm{ZAxis}]$$

Then, we used Matlab built-in function *global2localcoord* to transfer the positions from global rectangular coordinates to local rectangular coordinates.

One of the results from the outdoor experiment was the plots of the subject's trials. Since there was a new starting point and walking direction for each trial, the original plots of the subject's trials looked disorganized, as shown in Figure 8.

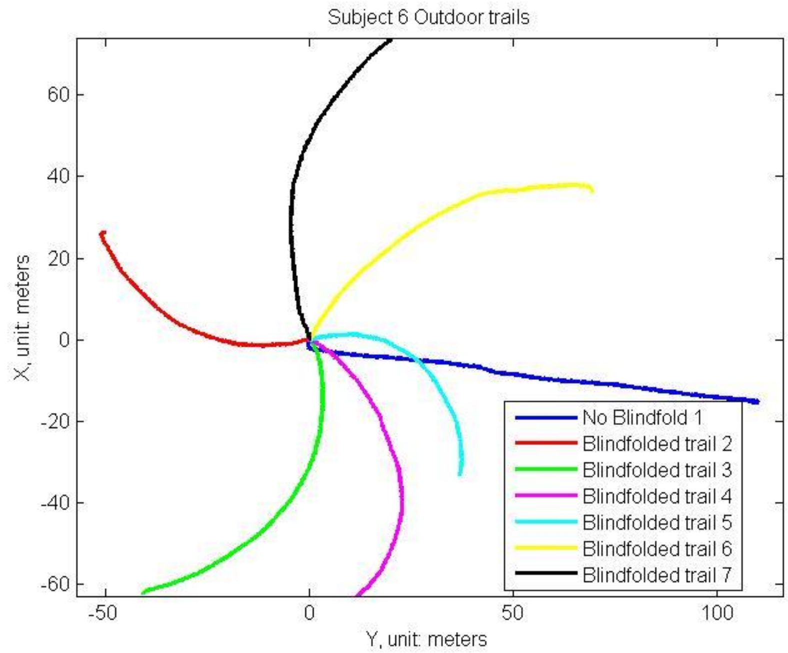

Figure 8: *Example of Original Outdoor Trials Plot*

In order to make the outdoor plots easier to understand, appropriate rotations were added to the trials plot as follows. For each subject, the walking direction of the eyes open trial was selected to be the standard walking direction for this particular subject. The walking directions of the blindfolded trials were defined as the tangential direction of the beginning sections (first 100 data points) of each trial. After calculating the angles between the standard direction and blindfolded directions, and rotate the blindfolded trials accordingly, the outdoor walking trials plot was more organized than before (Figure 9). It was much easier to observe the subject's behavior from the new plot.

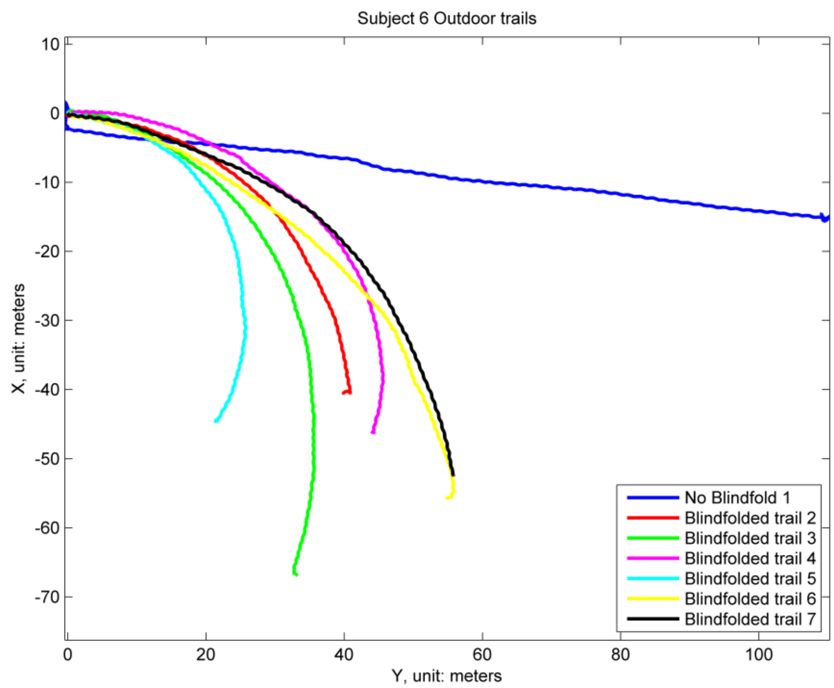

Figure 9: *Example of Organized Outdoor Trials Plot*

Due to the technical limitation of the GPS as well as the natural velocity fluctuations in human walking, the data collected from the outdoor experiment had some inherent noises and variability as shown in Figure 10. These noises and within-step were ignored in the calculation of angular velocities and curvatures of the walking paths as follows. First, every 50 data points (5 seconds) were set as one data group. The tangential direction of one data group was the average of the sum of the tangential directions at each of the 50 data points within that group. Then the angle between two tangential directions of two groups was the angle veered during the time period of 50 data points, which equals to 5 seconds. The average angular velocity was then calculated as the change in tangent direction angle divided by the corresponding time duration.

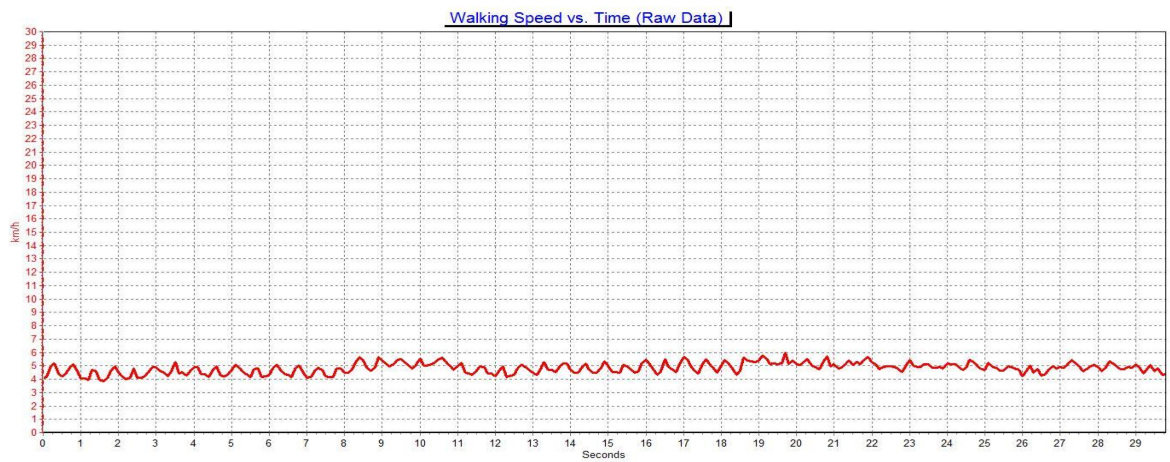

Figure 10: *Example of the inherent noise from VBOX mini GPS.*

3.2 Indoor Experiment Data Processing

The indoor data were processed mainly using Vicon Nexus. As mentioned in Chapter 2, each indoor trial only had about 5 steady state walking steps that were useful for mathematical model generation. Even though the starting and end points were set beyond the capturing range of the Vicon cameras, sometimes the subjects still started or stopped within the camera range, especially during the blindfolded trials. Therefore, manually picking the usable walking sections were necessary. The location of each marked body part was represented by the weighted sum of the three markers on them. Each marked body part should have at least 2 markers visible from the Vicon Nexus monitoring screen to provide an accurate position of the body part. Based on the above rules, first two steps after start, last two steps before full stop as well as the sections without at least two stably visible markers were excluded from the collectable data.

Next, a simplified human body model was constructed in Vicon Nexus. The human body model consisted of three segments, namely torso, right foot and left foot. Markers on each segment were named correspondingly (Torso1, Torso2, Torso3, etc.). The segments were connected using ball joints to provide 3 degrees of freedom per joint. The model is shown in Figure 11.

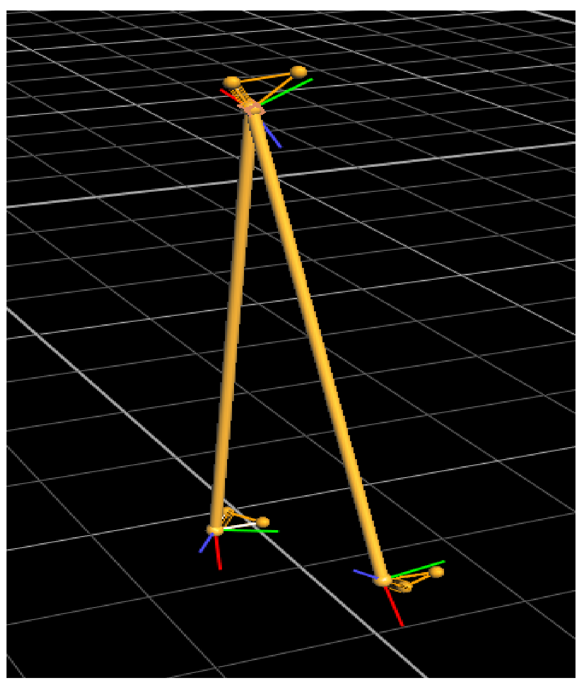

Figure 11: *Simplified Human Body Model built in Vicon Nexus*

Chapter 4: Model Generation

4.1 Key elements when describing the walking motion with torso and foot positions

Our goal is to obtain a simple model, from the indoor motion capture data, that gives the next body torso position and heading angle given the current torso position and heading angle.

Global Coordinate System: As mentioned in Chapter 2, the global origin of Vicon motion capture cameras was set approximately at the center of the capturing range. The global coordinate system is defined as follows: If the subject is facing squarely against the opposite wall, then the global Z axis is vertical upwards, the global X axis is lateral pointing to the left of the subject, and global positive Y is pointing against the face of the subject. These axes are consistent through the indoor experiment and do not rotate relative to the ground.

Stance foot, Swing foot: Here, the stance foot is defined as the foot on the ground during each step and the swing foot is the one moving forward.

Local Coordinate System: To better relate the adjacent stance feet positions, each stance foot has its local coordinate system. The local Z axis is vertical upwards and the local Y axis is pointing in the direction of torso velocity vector in the global XY plane. Then the local X axis is the cross product of Y and Z axes. The origin of the local coordinate system is the current stance foot position in the global coordinate system.

Mid-stance of the gait cycle: The “mid-stance” of each stance phase is defined as when the torso has the same local y position as the stance foot. The central mathematical model in this research uses the mid-stance body state of the current stance foot to predict the mid-stance body state of the next stance foot on the same side.

Key ingredients of the mathematical model. From the indoor walking data, we computed the torso movement position vectors from one (left) mid-stance to the next (left) mid-stance in the local coordinate system of the current (left) stance foot were calculated. The torso angle change between two mid-stances was also calculated. Next, from the tens of mid-stances in the indoor trial, we computed the mean values and the standard deviations of the torso position change and torso angle change from one mid-stance to the next.

4.2 Procedure of Simulation

Once we generate a model for one stride from the indoor mocap data, we then “simulate” this model for a 100 strides so as to see if this simulates similar curved-walking behavior as in our outdoor experiments.

Given some initial mid-stance position, the mathematical model predicts the next mid-stance position by generating a random position from a normal distribution of mid-stance torso position vector with mean and standard deviation calculated based on indoor experiment data. Similarly, the next torso angle (defining the local coordinates) is obtained by adding to the current torso angle, a random number with mean and standard deviation obtained from indoor walking data. To generate a simulated trial, each mid-stance torso position will first be simulated in the local coordinate system of the previous mid-stance. The newly generated mid-stance will then be used as the new local coordinate system to simulate the next mid-stance torso position. After all the mid-stance torso positions are simulated, they will be transfer back to the global coordinate system to plot out the simulated trial.

Chapter 5: Observations and Results

5.1 Outdoor Experiment Results

The main results of the outdoor experiment were the walking route plots. The walking route plots were divided into different groups that showed some different behaviors.

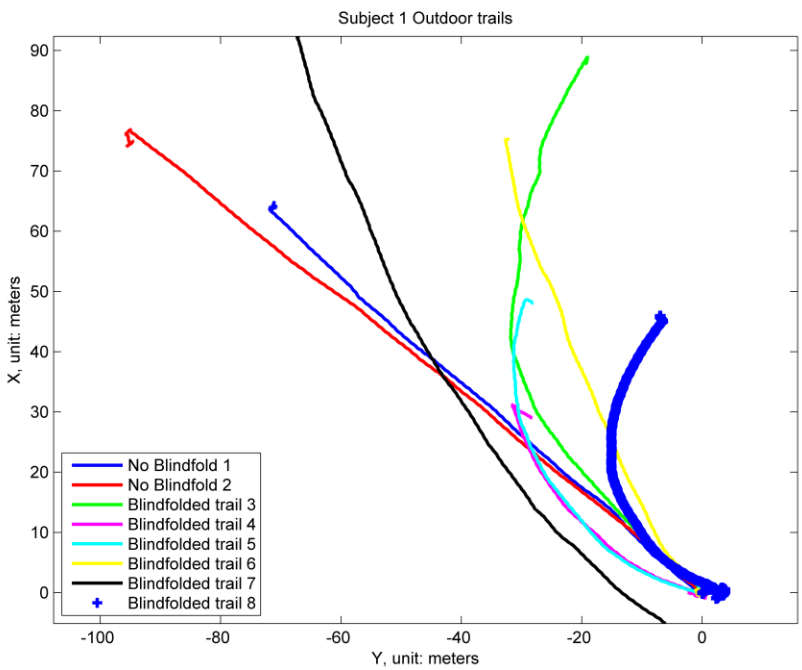

Figure 12: *Subject 1 Outdoor Trails Plot*

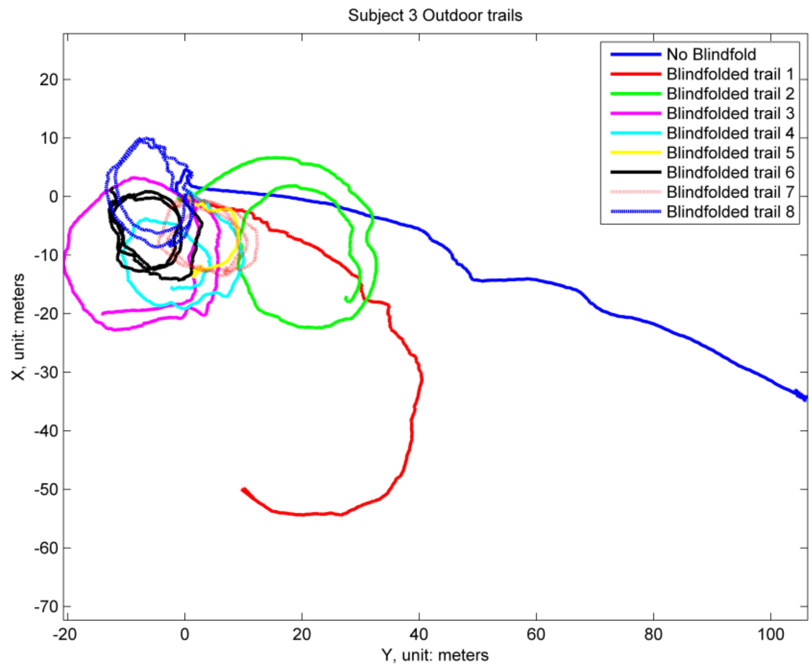

Figure 13: *Subject 3 Outdoor Trails Plot*

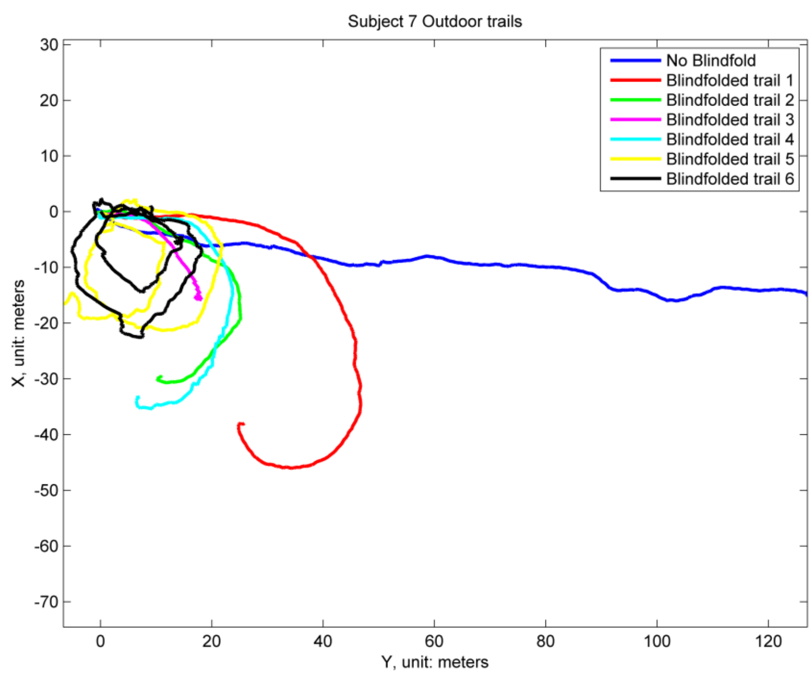

Figure 14: *Subject 7 Outdoor Trails Plot*

Figures 12, 13 and 14 show the outdoor route plots of three subjects. These subjects all showed similar blindfolded walking behaviors. During the experiment, the subjects only veered to one side (right). As the blindfolded time got longer, the walking stability of the three subjects became worse as their walking path radius went smaller and smaller.

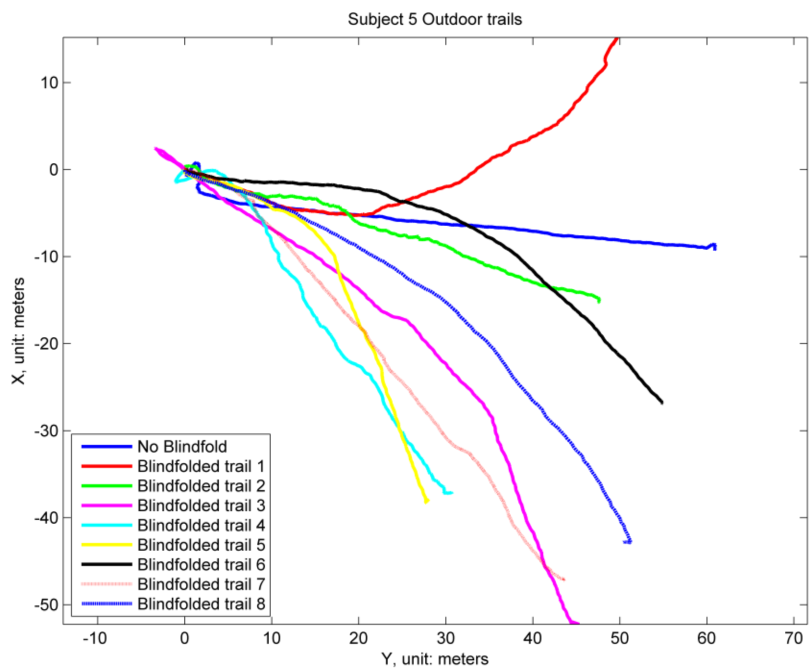

Figure 15: *Subject 5 Outdoor Trails Plot*

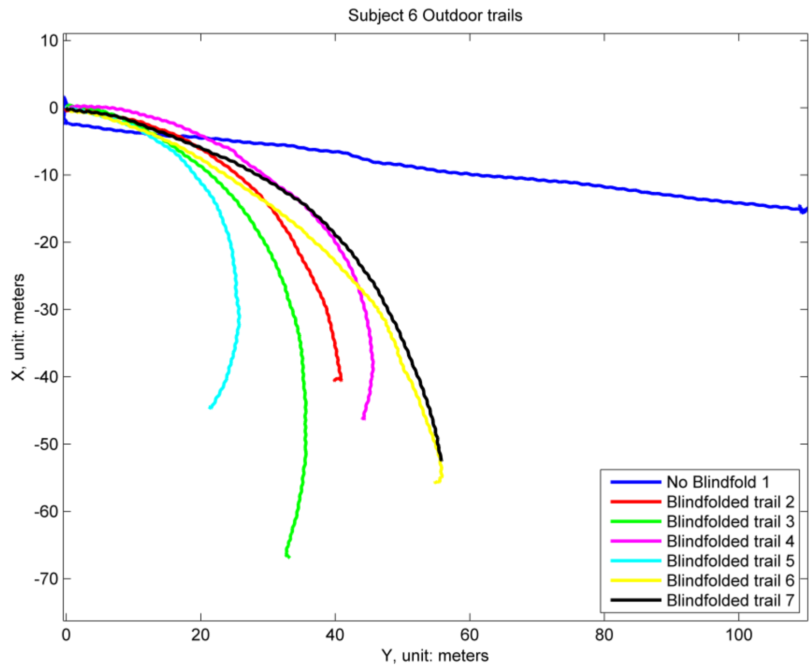

Figure 16: *Subject 6 Outdoor Trails Plot*

Figures 15 and 16 show the walking route plots of two other subjects. These two subjects also had a preferred veering direction to the right as the previous three subjects. However, their walking stabilities were not obviously affected by the blindfolded time. The curvatures of their walking routes were steady through the experiment.

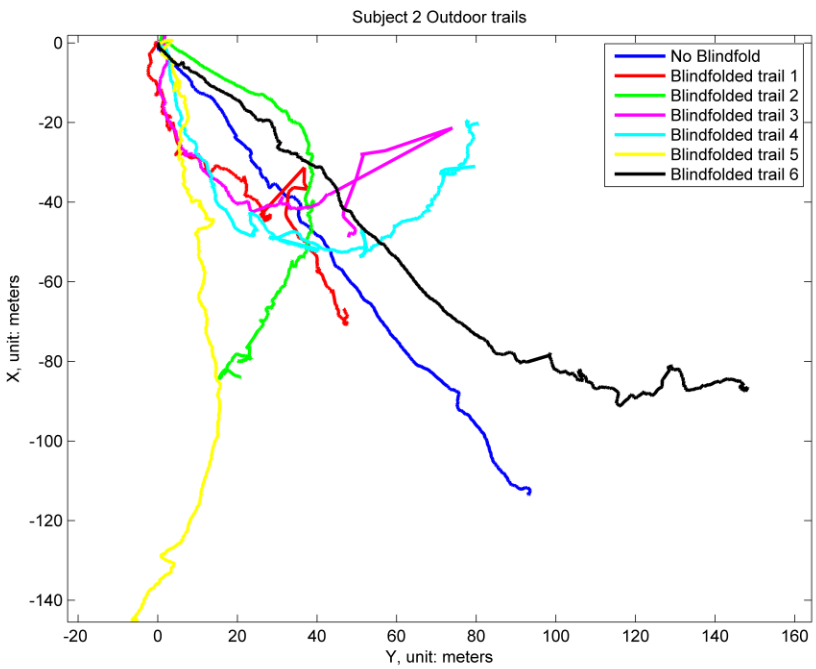

__Figure 17:__ Subject 2 Outdoor Trails Plot

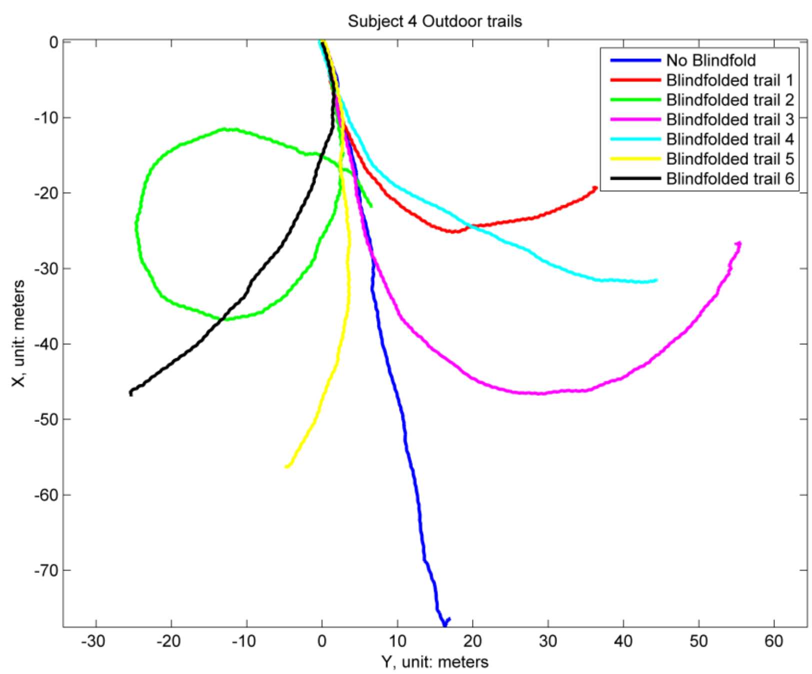

__Figure 18:__ Subject 4 Outdoor Trails Plot

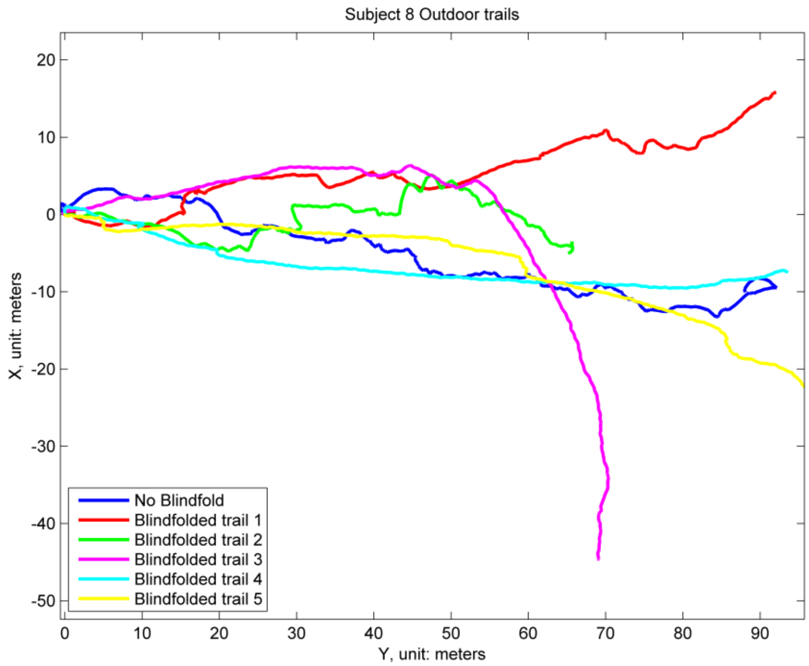

Figure 19: *Subject 8 Outdoor Trails Plot*

Figures 17, 18 and 19 show the walking routes of the last three subjects. These subjects showed completely different waking behavior with the previous five subjects. These subjects veered in both directions during the experiment and the changing tendency of the curvatures of their trials was not clear. Their walking directional stabilities were very unstable and showed hardly any connection to the blindfolded time.

3 out of the 8 subjects didn't have a preferred veering direction as their trials went in both left and right directions multiple times. Their walking stability seemed very unstable and showed no sign of connection with the total blindfolded time. The

remaining 5 subjects all seemed to have a preferred veering direction to the right. 3 out of these 5 subjects showed a trend of getting worse walking stability as the total blindfolded time went longer. The remaining 2 of them showed a relatively steady walking stability. Interestingly, no one in the experiment had a preferred veering direction to the left. None of the subjects changed the veering direction within a single trial (even if they used different veering directions in different trials). If the subject started veering in one direction, he/she would keep veering in that direction through the trial.

Table 1: *Average Angular Velocity and Curvatures of Outdoor Trails*

Subject #	Average Angular Velocity (rad/s)	Average Curvature (1/m)
1	0.1469	0.1527
2	0.1002	0.2153
3	0.1104	0.1828
4	0.0440	0.0642
5	0.0475	0.1057
6	0.0416	0.0611
7	0.1388	0.1726
8	0.0485	0.1600

Average angular velocities and average curvatures for each subject during the outdoor experiment were calculated using the weighted data points as described in Chapter 3 in order to reduce the effect of inherent noise from the GPS. However, there is still some noise in the outdoor data so that the average angular velocities and curvatures in Table 1 may not perfectly reflect the actual outdoor behavior of the subjects.

5.2 Indoor Motion Capture Experiment Results

The purpose of the indoor experiment was to collect data necessary for the model generation. Five of the subjects that participated in the outdoor experiment also joined the indoor experiment. This section shows the processed indoor data including the mean and standard deviation of torso angle changes, number of stance foot transitions, histograms of the torso angle changes as well as the torso positions during the trials.

Table 2: *Mean and Standard deviation of Torso angle change over all indoor blindfolded trials*

Subject #	Mean Torso Angle change over one stride, rad	Standard deviation of Torso Angle change over one stride
1	-0.0100	0.0484
2	0.0076	0.0505
3	-0.0057	0.0432

4	0.0231	0.0675
5	0.0211	0.0697

Table 3: *Number of Stance foot transitions on both sides over all blindfolded trials*

Subject #	Left to left transitions	Right to right transitions
1	60	52
2	32	36
3	32	34
4	54	46
5	40	38

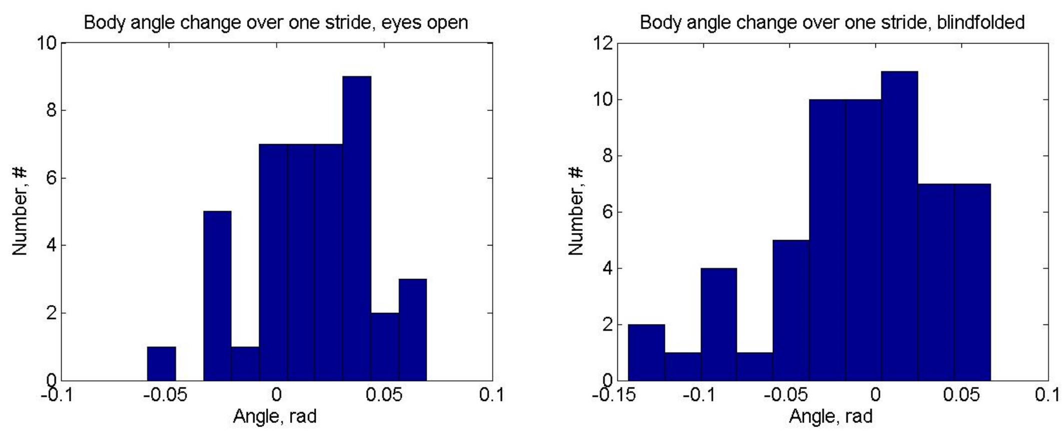

Figure 20: *Subject1_ Histograms of Torso Angle Change over One Stride*

(L: Eyes Open, R: Blindfolded)

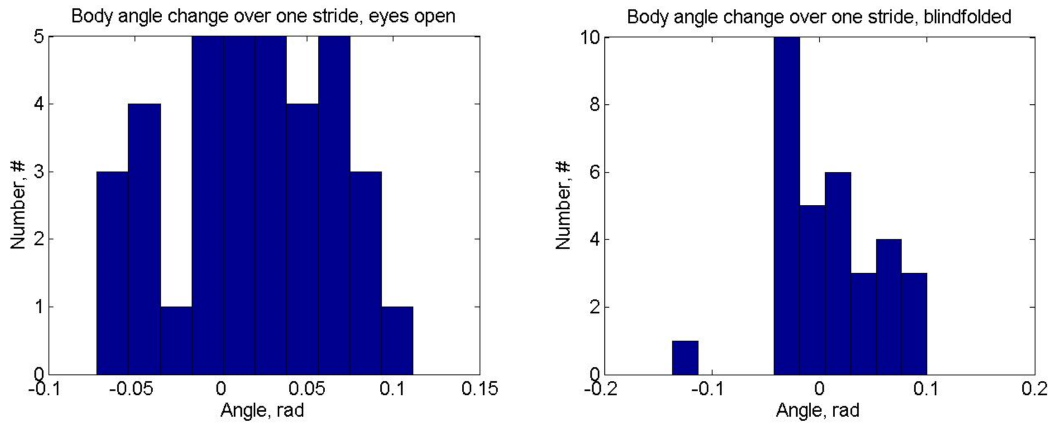

Figure 21: *Subject2_ Histograms of Torso Angle Change over One Stride*

(L: Eyes Open, R: Blindfolded)

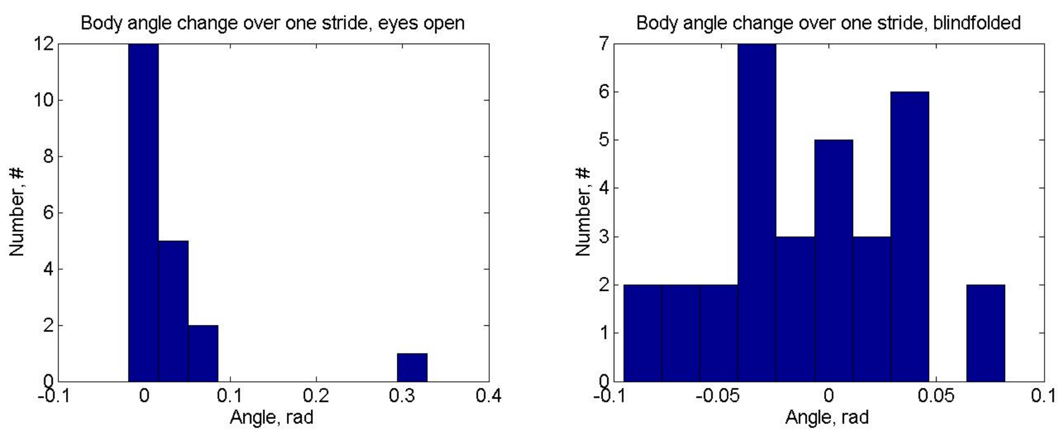

Figure 22: *Subject3_ Histograms of Torso Angle Change over One Stride*

(L: Eyes Open, R: Blindfolded)

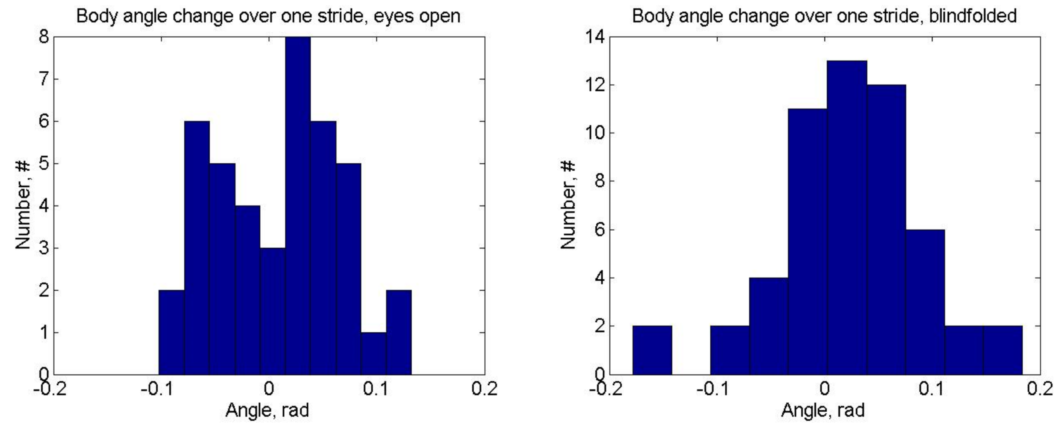

Figure 23: *Subject4_ Histograms of Torso Angle Change over One Stride*

(L: Eyes Open, R: Blindfolded)

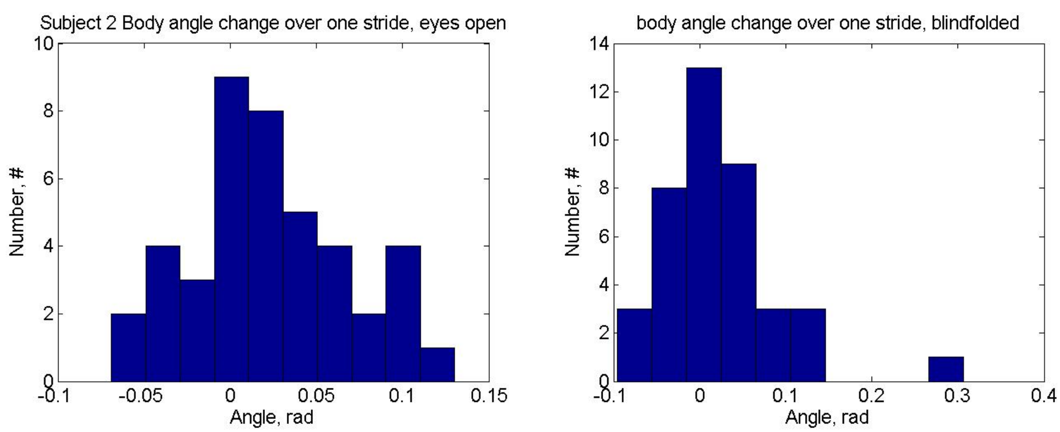

Figure 24: *Subject5_ Histograms of Torso Angle Change over One Stride*

(L: Eyes Open, R: Blindfolded)

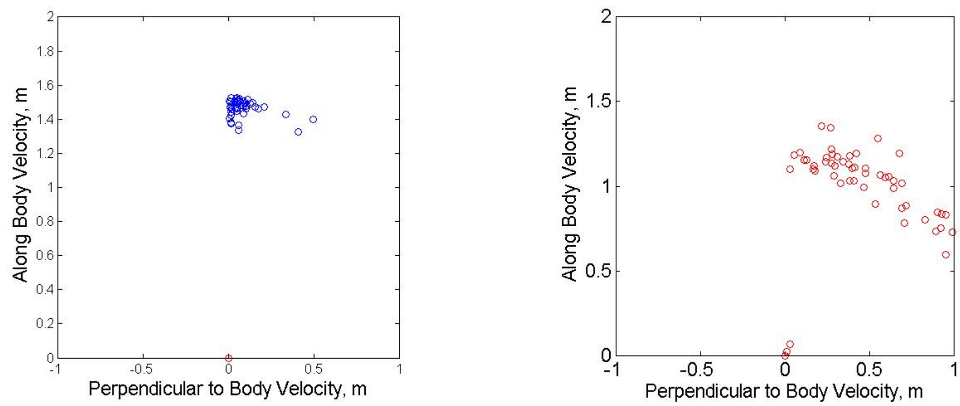

Figure 25: *Subject 1_Torso Positions relative to previous stance foot position in a body-based local coordinate system*

(L: Eyes Open; R: Blindfolded. Same for other plots)

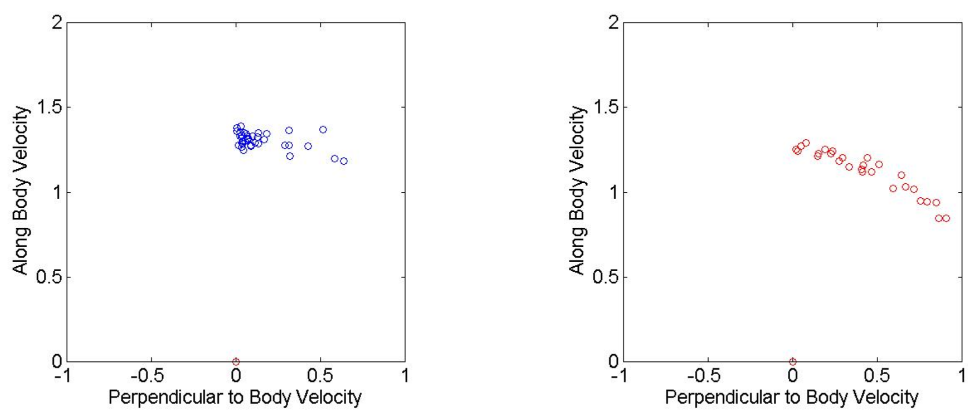

Figure 26: *Subject 2_Torso Positions relative to previous stance foot position*

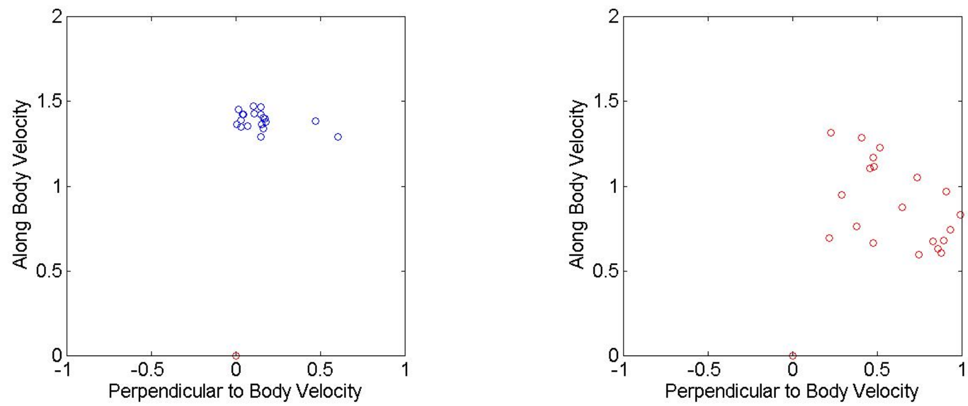

Figure 27: *Subject 3_Torso Positions relative to previous stance foot position*

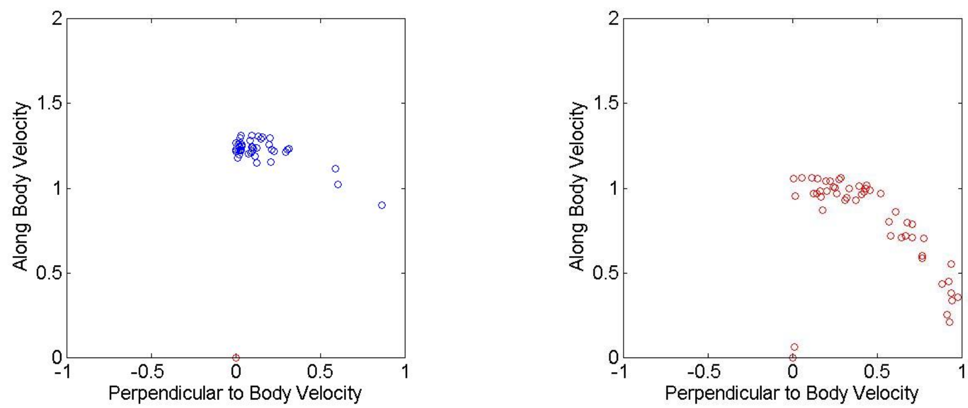

Figure 28: *Subject 4_Torso Positions relative to previous stance foot position*

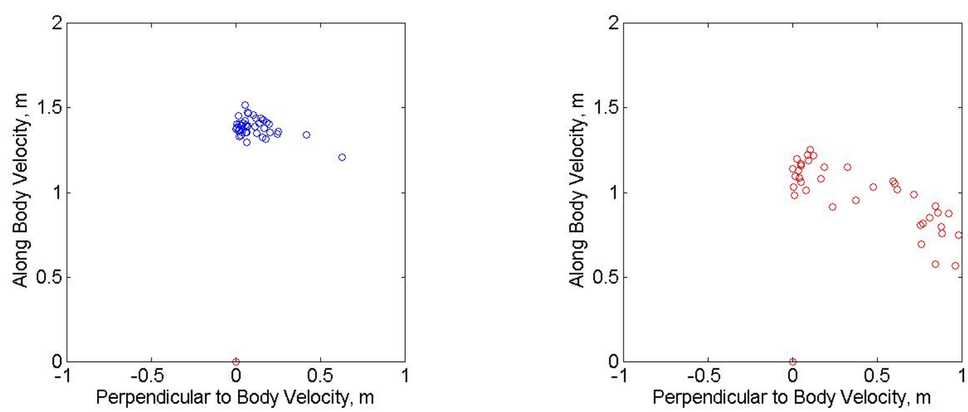

Figure 29: *Subject 5_Torso Positions relative to previous stance foot position*

5.3 Model Simulation Results

Five simulated trials with 100 steps each were simulated for each subject who participated in the indoor experiment using the mathematical model. These simulated trials are compared with the outdoor trials to study the relevance and identify the deficiencies of the model.

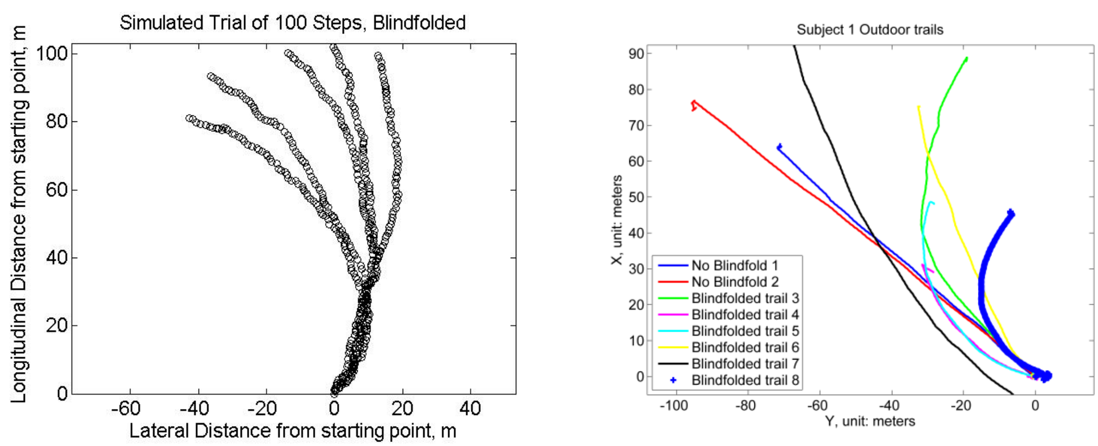

Figure 30: *Subject 1_Simulated Trials vs. Experimental Trials*

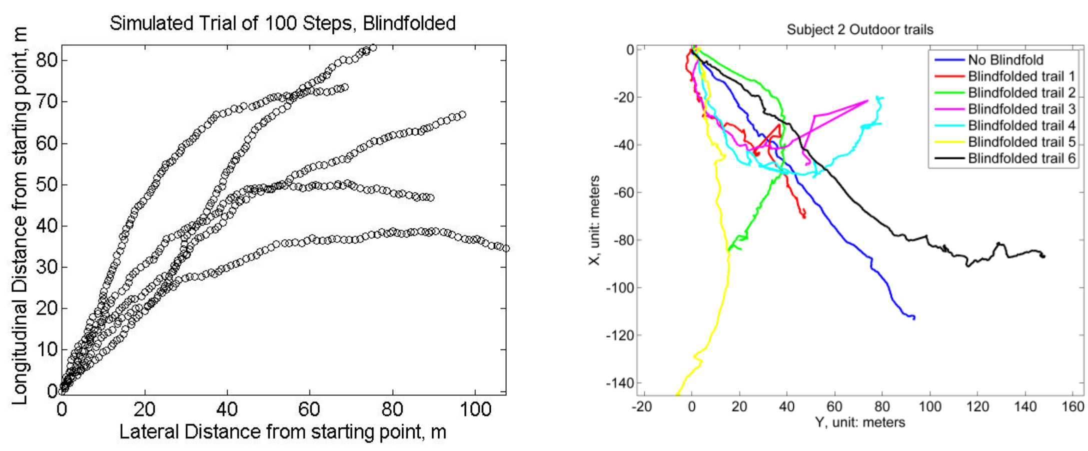

Figure 31: *Subject 2_Simulated Trials vs. Experimental Trials*

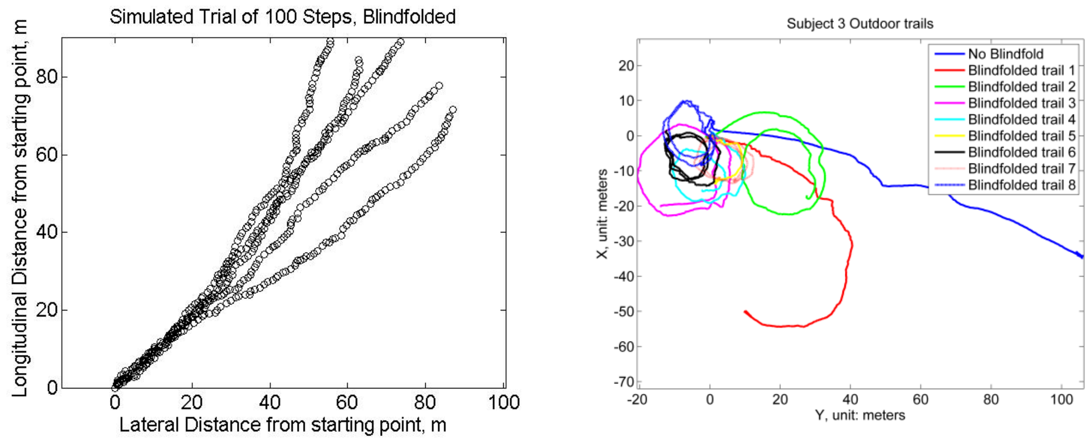

Figure 32: *Subject 3_Simulated Trials vs. Experimental Trials*

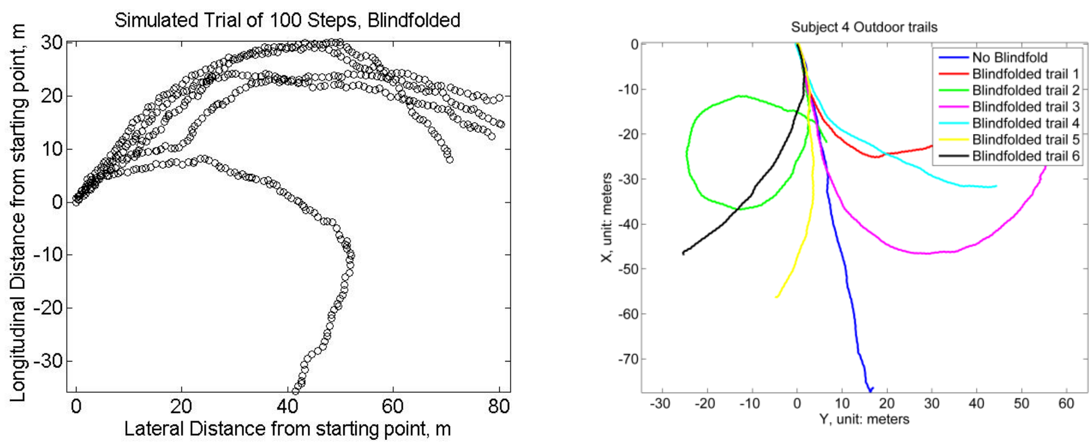

Figure 33: *Subject 4_Simulated Trials vs. Experimental Trials*

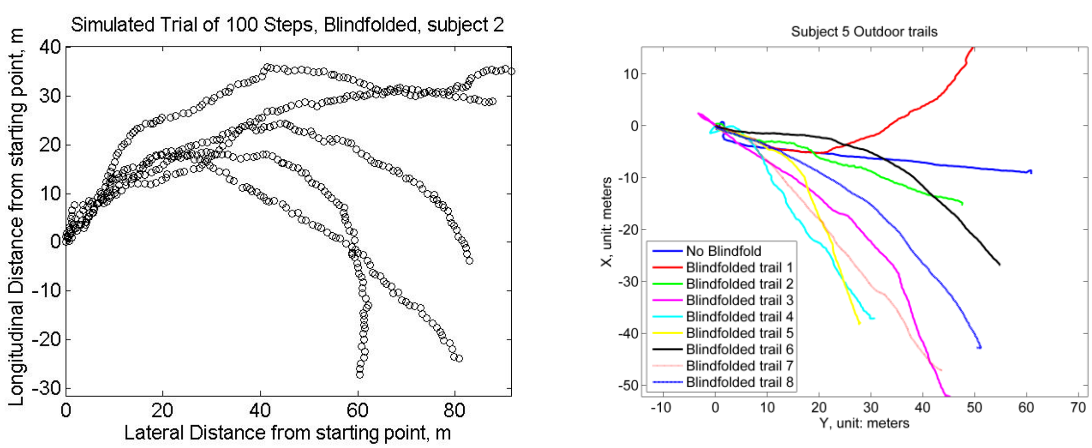

Figure 34: *Subject 5_Simulated Trials vs. Experimental Trials*

5.4 Qualitative Analysis of the mathematical model simulations

Since the mathematical model was built using the data collected during the indoor experiment, the simulated trials can reflect the walking behaviors of the subjects during the indoor experiment to some extent. The simulated trials of these subjects show different walking behaviors comparing to their outdoor trials. For example, no one in the outdoor experiments showed a veering preference to the left. However, the simulated trials of two subjects veered to the left as shown in Figure 30 and 32.

Another inconsistency shown between the simulated trials and the experimental trials is the connection between walking stability and total blindfolded time. Subject 2 and subject 3 (as in Figure 31 and 32) had poorer walking stability comparing to subject 4 and subject 5 (as in Figure 33 and 34) during the outdoor experiments. However, the simulated trials of subject 2 and 3 show a much better walking stability than the simulated trials of subject 4 and 5, judging by the curvatures of the plots. It was possible that during the indoor experiment, the subjects only walked very short distances compared to the outdoor experiments that were not long enough to capture the real walking behavior after a long blindfolded time. Of course, the model did not explicitly use the duration of time blind-folded as an input, so is anyway unable to predict the effect of the blind-folded time. In addition, the subjects were interrupted every time they reached the end of the room or walked out of the capturing range of the Vicon cameras. The inherent noises in their vestibular systems were presumably accumulating intermittently, and perhaps not continuously as was the case during outdoor experiments. These effects might have affected their blindfolded walking behavior and caused the differences between model and outdoor experiment.

The mathematical model also has the inability to simulate trials that veer in both directions for the same subject. The model was built based on the mean and standard deviation of the torso angle changes of the subject. For this reason, the veering direction of the simulated trials was already known even before the simulation. If the subject had a positive mean torso angle change, his/her simulated trial would almost surely veer to the right.

Chapter 6: Conclusion and Future Plans

The purpose of this research was to study the human walking behavior without vision by a combined method of experiments and mathematical modelling. In order to replicate the no vision condition, the subjects were blindfolded during the experiments. The research had two experiments designed to collect data that can be used to describe human walking behavior. A very simple mathematical model has been built, using the normal distribution of torso angle change during one stride with calculated mean and standard deviation from the experimental data, to simulate the blindfolded walking behavior. Although the model is unable to perfectly simulate the highly complicated human blindfolded walking behavior, it provides a prototype of the mathematical modelling approach to study the problem. Other than the mathematical model, the research also discovered some interesting walking behaviors in experiment as discussed in Chapter 5 that seems worth studying further.

Future studies can focus on improving the model by applying more complicated mathematical theories to better reflect the true human walking behavior. For example, instead of using normal distribution prediction, one may use linear regression method or non-linear regression method to obtain a mapping from one mid-stance state to the next using more state variables (e.g., position, velocity, orientation, and angular velocity of various body segments). The indoor experiment in this research was restricted by the limited area of the room. Future researchers may repeat this experiment in a bigger room that will allow the subjects to walk continuously for a long time without being interrupted. Doing this may allow the subjects to act more like what they did in the outdoor experiment, thus improving the data accuracy of the indoor experiment and eventually improving the quality of the mathematical model.

Other than improving the model, the observations made during the experiments worth further studying. For example, no subject had a preferred veering direction to the left during the outdoor experiment. However, the indoor experiment data showed that at least two subjects veered to the left more than to the right when walking indoor. The reason behind this inconsistency is not clear and requires more study. During the outdoor experiments, some subjects seemed to have a tendency to perform worse as the blindfolded time increased, some subjects had relatively steady walking stability that their performances were not seriously affected by the total blindfolded time, and others had very unstable walking stability that their performances changed all the time and showed barely any connection with the blindfolded time. Future studies may look into this phenomenon and find the reasons that lead to these differences.

Overall, this research provided a simple mathematical approach to study the human blindfolded walking behavior. It also discovered some currently inexplicable walking behaviors that worth future studies. We hope that further research on veering in blindfolded walking will enable assistive devices that enable prevention or control of veering during blind-folded walking or indeed walking of individuals with visual impairments

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